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Effects of Ozone and Water Stress, Separately and in Combination, on Soybean Yield

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A primary concern in applying existing O_3-effects data on crop production is the relatively unknown influence of soil moisture which may modify plant response to O_3. One of the deficiencies in performing field experiments to test the influence of soil moisture on crop response to O_3 has been the lack of control of soil moisture conditions in open-top chamber plots. Most experiments have relied on the occurrence of normal drought periods during the growing season and use of irrigation to adjust soil moisture conditions. This has not allowed the control of the water stress cycles that is desirable. In 1986 a field experiment was performed with soybean [Glycine max. (L.) Merr. cv. Young] to test the influence of moderate water stress on the yield response to O_3. Open-top field chambers were used to expose plants to a range of O_3 concentrations, and rain exclusion caps were used on individual chambers to help regulate soil moisture levels. There were three soil moisture treatments [well-watered (WW), water-stressed (WS), and well-watered with permanent rain exclusion caps that were in place from 35 days after planting until physiological maturity (WW-C)]. In the WW and WS treatments, the rain caps were put in place only during an exceptionally wet period from mid-August to mid-September. The WW and WW-C treatments had approximately the same yield and a similar response to O_3, indicating that the presence of the caps for most of the growing season had little effect on growth or sensitivity to O_3. The WS plots yielded 15 to 18% less than the WW and WW-C plots, but water stress did not change the relative response to O_3 (i.e., no significant O_3 x water interaction). Based on a Weibull dose-response model, O_3 reduced the yield of 'Young' soybean 13% at a concentration of 0.05 uL L^{-1} (12 h d^{-1} seasonal mean) compared to a hypothetical background of 0.02 uL L^{-1}. This compares to previous estimates of 4 to 20% loss with other soybean cultivars at similar doses.

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Effects of Ozone and Water Stress, Separately and in Combination, on Soybean Yield

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ABSTRACT

A primary concern in applying existing O_3-effects data on crop production is the relatively unknown influence of soil moisture, which may modify plant response to O_3. One deficiency in field experiments that have tested the influence of soil moisture on crop response to O_3 has been lack of control of soil moisture conditions in open-top chamber plots. Most experiments have relied on the occurrence of normal drought periods during the growing season and use of irrigation to adjust soil moisture conditions. This has not allowed the control of the water stress cycles that is desirable. In 1986 a field experiment was performed with soybean [*Glycine max.* (L.) Merr. cv. Young] to test the influence of periodic water stress on the yield response to O_3. Open-top field chambers were used to expose plants to a range of O_3 concentrations, and rain exclusion caps were used on individual chambers to help regulate soil moisture levels. Three soil moisture treatments were used [well-watered (WW), water-stressed (WS), and well-watered with permanent rain exclusion caps that were in place from 35 d after planting until physiological maturity (WW-C)]. In the WW and WS treatments, the rain caps were put in place only during an exceptionally wet period from mid-August to mid-September. The WW and WW-C treatments had approximately the same yield and response to O_3, indicating that the presence of the caps for most of the growing season had little effect on growth or sensitivity to O_3. The WS plots yielded approximately 10% less on the average than the WW and WW-C plots, but water stress did not change the response to O_3 (i.e., no significant $O_3 \times$ water interaction). Based on a Weibull dose-response model, O_3 reduced yield of 'Young' soybean 13% at a concentration of 0.05 $\mu L\ L^{-1}$ (12 h d^{-1} seasonal mean) compared to a hypothetical background of 0.02 $\mu L\ L^{-1}$.

SOYBEAN [*Glycine max* (L.) Merr.] is known to be sensitive to the atmospheric air pollutant ozone (O_3) and yield suppression of approximately 5 to 15% has been projected at current ambient levels of O_3 (Heck et al., 1984b). One primary concern in the use of existing data of O_3 effects on crop production in the estimation of regional or national impacts is the relatively unknown influence of environmental factors (e.g., climate, soil type, management practice) on the yield response to O_3. Year-to-year and site-to-site variation in response of crops to O_3 is known to occur, but the extent of the variation under a range of environmental conditions is not well understood. Soil moisture has been considered one of the more important factors that modifies plant response to O_3, because it influences O_3 uptake through the stomata (Tingey et al., 1982, Tingey and Hogsett, 1985; Amundson et al., 1986).

Several studies have examined the influence of soil moisture on yield response of soybean to O_3 under field conditions (Heagle et al., 1988). In some cases water stress reduced yield suppression caused by O_3 (Heagle et al., 1987; L.W. Kress, 1988, personal communication), whereas in other cases the impact of O_3 was not altered by water stress (Heagle et al., 1987). In one case, with very mild water stress, the O_3 suppression of soybean yield at near ambient O_3 concentrations was greater under water-stressed conditions than with optimum soil water (Heggestad et al., 1985). These studies were performed at different locations under a variety of growing conditions and sometimes with different cultivars, so generalizations from the results are difficult to make.

Some experiments testing the effects of water stress on response of crops to air pollutants have relied on the occurrence of drought periods and have used different amounts of irrigation to adjust soil moisture conditions in well-watered and water-stressed treatments (Heagle et al., 1987). Although this approach works in regions where periods of drought typically occur during the growing season, it does not allow control of timing or extent of the drought cycles. In a few experiments rain has been excluded from open-top chamber plots. For example, plastic shields suspended above chambers during periods of rain and plastic sheeting permanently installed 10 cm above the soil over part of the chamber plot area have been used (Heggestad et al., 1985). Other approaches to the exclusion of rain have been used, such as permanently installed (Hogsett et al., 1985) or removable covers (Johnston et al., 1986; L.W. Kress, 1988, personal communication). Little is known, however, concerning the potential of any of these exclusion techniques for modifying plant response to air pollutants.

In our efforts to assess the impact of O_3 on crop productivity, information is required concerning the O_3 sensitivity of a wide genetic base for common crops such as soybean (Heck et al., 1984a). For this reason and for the needs stated previously, the following objectives were addressed in this field study with soybean that was done in conjunction with the National Crop Loss Assessment Network: (i) determine the effects of moderate water stress on O_3 dose-response relationships; (ii) determine the effects of O_3 on the yield response of a previously untested cultivar of soybean; and (iii) test a technique for excluding rain in open-top chamber plots in order to more precisely control soil moisture conditions and to determine if this technique modifies plant response to O_3.

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METHODS AND MATERIALS

Plant Growth

The experiment was performed in a field of Cecil-Appling soil (clayey, kaolinitic, thermic, Typic Hapludults) located 8 km south of Raleigh, NC. The field was fertilized with 392 kg ha^{-1} of 0–8.74–16.6, N–P–K (0–20–20) according to soil test recommendations and treated with the recommended rate of trifluralin (α, α, α-trifluoro-2,6-dinitro-*N*,*N*-dipropyl-*p*-toluidine). 'Young' soybean (maturity group VI) seeds were inoculated with *Bradyrhizobium japonicum* ('S' strain, Nitragin Co., Milwaukee, WI) and planted at a 76-cm row spacing on 5 June 1986. Plots (four 3-m rows) were selected based on stand uniformity on 20 June and thinned to 12 to 13 plants m^{-1} of row on 1 July. Insects and mites were controlled with recommended rates of permethrin [3-(phenoxyphenyl) methyl (1RS) -cis, trans-3(2,2-dichloroethenyl)-2,2-dimethyl cyclopropane carboxylate] and dimethoate [*O*,*O*-dimethyl *S*-(*N*-methylcarbamoylmethyl) phosphorodithioate].

Ozone and Soil Moisture Treatments

Dispensing and monitoring of O_3 in open-top chambers was done as described previously (Heagle et al., 1979, 1986). Five O_3 concentrations were used: charcoal-filtered (CF), nonfiltered (NF), and three proportional additions of 1.5, 1.8, and 2.1 times the ambient air (AA) concentration (AA × 1.5, AA × 1.8, and AA × 2.1, respectively). Ozone additions were made between 0800 and 2000 h EST when ambient O_3 concentrations exceeded 0.03 $\mu L\ L^{-1}$. Ozone treatments began on 2 July and continued through 16 October. Ozone was not dispensed for approximately 11% of the available dispensing time due to monitor calibration, irrigation, or system malfunction.

Rain exclusion caps were used in the experiment to help in the control of soil moisture conditions. The cap consisted of a transparent polyvinyl chloride circle (cover), which was attached over a dome-shaped tubular frame. The frame was circular (3.8 m in diam. with a 51-cm height at the center of the dome and mounted 41 cm above the top of the chamber). The frame was permanently installed on the open-top chambers, but the cover was removable. The 41-cm space between the rain exclusion frame and the top of the chamber was left open to allow the flow of air that is necessary for open-top chambers. The design is similar to that used by Hogsett et al. (1985), except for the cap dimensions and the absence of a frustum on our chambers.

Three types of soil moisture treatments were used in the study. In one set of plots the rain exclusion covers were left in place continuously from 10 July to 24 October as a test of the effects of the caps on plant growth and yield. This treatment was maintained under well-watered conditions and is designated the well-watered capped treatment (WW-C). In two other sets of plots, the cover was installed when needed to exclude rain. One set of plots was well-watered (WW) and the other periodically water-stressed (WS). Due to an unusually rainy period from early August until early September (Table 1), the covers were left on these plots from 11 August to 13 September. After that time there was very little rain and the covers were not reinstalled. To minimize surface runoff entering the plots during heavy rainfall, soil was banked to a height of approximately 15 cm around the base of each chamber. Soil moisture in the WW and WW-C treatments was maintained as similar as possible by irrigation to allow comparisons of growth, yield, and response to O_3 in these plots.

Soil moisture conditions were maintained in all treatments by irrigation with an overhead spray system. The irrigations were applied during periods of low O_3 concentrations (either early morning, late afternoon, or when the O_3 delivery was turned off). The need for irrigation was determined with neutron probe (Model 503, Campbell Pacific Nuclear, Pacheco, CA) and tensiometer (Irrometer Co., Riverside, CA) measurements at a depth of 15 to 18 cm. Soil matric potential was estimated from neutron probe readings using soil moisture retention curves derived from soil taken from the appropriate depth in each plot. Measurements were not made at a greater depth because the majority of the roots were in the topsoil, which had an average depth of about 23 cm. Also, previous experience has shown that measurements in

Table 1. Summary of environmental conditions, irrigation, and plant growth stages on a monthly basis.

Variable	Moisture treatment†	O_3 treatment‡	Month					Total
			June	July	Aug.	Sept.	Oct.	
Mean max. temp., °C	Ambient	Ambient	33.7	35.7	30.1	29.2	24.2	–
Mean min. temp., °C	Ambient	Ambient	19.5	21.6	19.6	17.6	11.8	–
Mean dew point temp., °C	Ambient	Ambient	13.0	14.2	16.4	17.6	10.8	–
Mean hourly PAR, $\mu E\ m^{-2}\ s^{-1}$	Ambient	Ambient	592	577	445	395	304	–
Monthly rainfall, cm	Ambient	Ambient	4.5	9.6	28.5	1.5	4.0	45.3
Rainfall in plots, cm§	WW, WS	All	4.5	9.6	1.8¶	0	4.0	19.9
	WW-C	All	4.5	2.6	0¶	0	2.5	9.6
Irrigation (cm)	WW	AA	0	11.4	10.0	20.3	7.6	49.5
		CF	0	15.2	11.4	24.1	15.2	66.0
		NF	0	15.2	11.4	24.1	11.4	62.2
		AA × 1.5	0	15.2	11.4	24.1	7.6	58.4
		AA × 1.8	0	15.2	11.4	24.1	7.6	58.4
		AA × 2.1	0	15.2	11.4	24.1	7.6	58.4
	WW-C	CF	0	15.2	14.0	20.3	11.4	60.9
		NF	0	15.2	14.0	20.3	11.4	60.9
		AA × 1.5	0	15.2	14.0	20.3	7.6	57.1
		AA × 1.8	0	15.2	14.0	20.3	7.6	57.1
		AA × 2.1	0	15.2	14.0	20.3	7.6	57.1
	WS	All	0	5.1	7.6	7.6	3.8	24.1
Plant growth stage#	WW, WW-C	All	VE–V5	V5–V19	V19–R5	R5–R6	R6–R8	–
	WS	All	VE–V5	V5–V17	V17–R5	R5–R6	R6–R8	–

† WW = well-watered; WS = water stressed; WW-C = well-watered with rain exclusion caps.

‡ Charcoal-filtered (CF), nonfiltered (NF), and three proportional additions of 1.5, 1.8, and 2.1 times the ambient air (AA) concentration (AA × 1.5, AA × 1.8, and AA × 2.1, respecuvely).

§ Ambient rainfall minus rain excluded with rain exclusion caps. Caps on 11 August to 13 September in WW and WS and 10 July to 24 October in WW-C.

¶ Two heavy rains brought plots to field capacity due to runoff. All plots also irrigated to assure equal soil moisture conditions among plots.

Growth stages estimated in the CF, AA × 1.5, and AA × 2.1 plots according to Fehr and Caviness (1977). In October, stage R8 was reached 1 to 3 wk sooner in the AA × 1.5 and AA × 2.1 plots than in the CF plots for all water treatments. Stage R8 was reached about 1 wk sooner in the WW-C as compared to the WW plots.

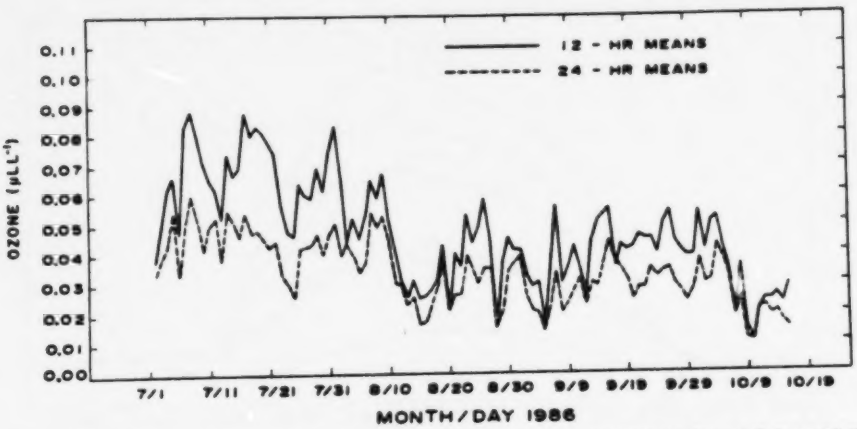

Fig. 1. Daily 12-h (0800–2000 h EST) and 24-h mean O_3 concentrations in ambient air from 2 July to 16 Oct. 1986.

the deeper clay layers did not adequately reflect the plant water status. Irrigation (2.5 or 3.8 cm) was applied when soil matric potential reached or became less than −0.03 MPa in the WW and WW-C plots or −0.3 MPa in the WS plots.

The effects of the open-top chambers, with and without the rain exclusion caps, on temperature and solar radiation were compared to a nonchambered plot. Temperature was measured with shielded thermocouples at five locations in the center two rows of the canopy at a height of 70 cm (the soybean plants were approximately 135 cm tall). Solar radiation was measured at a height of 140 cm with two tube solarimeters (Delta-T Devices, Type TSL), each positioned perpendicular to the soybean rows in the center of the chamber. Concurrent measurements were made in one of each plot type.

Plant Response Measures

Leaf water potential was measured on an approximately weekly basis with thermocouple psychrometers using chambers similar to those described by Brown and Collins (1980). Measurements were made on leaf punches (3.6 cm^2 total area) taken from the sixth trifoliolate (counting from the apex of the plant). Two leaves from both replicates of the CF, AA × 1.5, and AA × 2.1 plots in the WW and WS treatments were measured on each occasion. Foliar injury (total of % chlorosis and necrosis) was estimated on the eight uppermost, fully expanded leaves of two plants per plot on 12 and 26 September and 10 October. All plants were harvested for determination of yield components when the seed had reached harvest maturity (17–18 November). Two 0.75-m sections of row were harvested individually from each of the two center rows of each plot. Pods were removed by hand and the number of filled pods and seeds in each row segment were counted. The moisture content of seeds from all plots was determined at the time the seeds were weighed.

Statistical Analyses

The experimental plots were completely randomized with two replicates of all treatment combinations (i.e., five O_3 levels × three soil moisture treatments × two replicates) giving a total of 30 open-top chamber plots. Analysis of variance (AOV) for the yield components was performed to test for row and treatment effects and all interactions. Interactions of row position with the O_3 and water treatments occurred; however, the interactions were not systematic and were caused by excessive variability among the rows from 3 of the 30 plots. Thus, the means of all rows within plots were used for subsequent analyses. Ozone dose vs. seed yield curves were generated with polynomial and nonlinear Weibull models. In the Weibull model: yield $= \alpha \exp[-(O_3/\sigma)^c]$, where α is the maximum yield at 0 μL L^{-1} O_3, σ is the O_3 concentration when yield is 0.37 α, and c is a dimensionless shape parameter. In both the polynomial and Weibull regression analyses, the seasonal (period of O_3 addition) 12 h d^{-1} mean O_3 concentration was used as the independent variable. The Weibull model was fit to the yield data according to the approach presented by Rawlings and Cure (1985). All analyses were performed using the Statistical Analysis System (SAS Inst., 1985).

RESULTS

Ozone Concentrations

Ambient O_3 concentrations were high in July and early August, but a prolonged period of rainy weather reduced the levels for most of August and the concentrations remained relatively low for the rest of the growing season (Fig. 1). Mean seasonal 12 h d^{-1} O_3 concentrations (0800 – 2000 h EST) averaged 0.018,

Table 2. Ozone concentrations measured during exposure of 'Young' soybean to O_3 at different soil moisture levels.†

Soil moisture treatment§	O_3 treatment¶	12 h d^{-1} O_3 conc., μL L^{-1}		1 h d^{-1} peak O_3 conc.,‡ μL L^{-1}	
		Seasonal mean	Highest daily	Seasonal mean	Highest hourly
WW	CF	0.015	0.047	0.026	0.074
	NF	0.036	0.075	0.050	0.118
	AA × 1.5	0.057	0.135	0.085	0.207
	AA × 1.8	0.071	0.160	0.109	0.259
	AA × 2.1	0.083	0.188	0.128	0.308
	AA	0.040	0.088	0.056	0.135
WW-C	CF	0.019	0.050	0.030	0.078
	NF	0.039	0.081	0.054	0.135
	AA × 1.5	0.061	0.139	0.090	0.209
	AA × 1.8	0.070	0.158	0.106	0.253
	AA × 2.1	0.087	0.207	0.135	0.332
WS	CF	0.020	0.051	0.032	0.080
	NF	0.038	0.082	0.054	0.128
	AA × 1.5	0.059	0.132	0.087	0.207
	AA × 1.8	0.072	0.158	0.108	0.244
	AA × 2.1	0.084	0.196	0.129	0.317

† Each value is the mean from two plots except for the CF and NF treatments, which are from one plot; for the daily period 0800 to 2000 EST, from 2 July to 16 October 1986.

‡ The 1 h d^{-1} peak is defined as the largest mean of two consecutive 3-min samples taken at 45-min intervals from 0800 to 2000 EST.

§ WW = well-watered; WW-C = well-watered with rain exclusion caps; WS = water stressed.

¶ Charcoal-filtered (CF), nonfiltered (NF), and three proportional additions of 1.5, 1.8, and 2.1 times the ambient air (AA) concentration (AA × 1.5, AA × 1.8, and AA × 2.1, respectively).

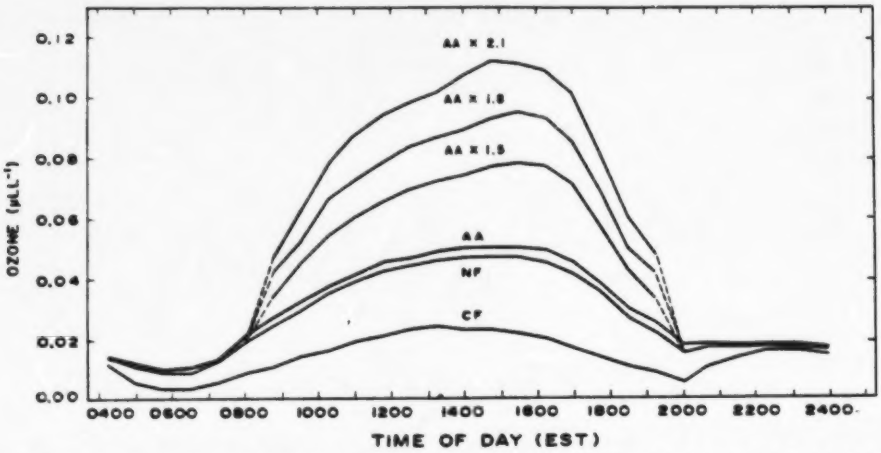

Fig. 2. Mean seasonal diurnal O_3 concentrations. CF = charcoal-filtered air; NF = nonfiltered air; AA × 1.5, AA × 1.8, and AA × 2.1 = NF air + the proportional additions of O_3; AA = ambient air. Curves are means over 2 July to 16 October dispensing period.

0.038, 0.059, 0.071, and 0.085 μL L^{-1} in the CF, NF, AA × 1.5, AA × 1.8, and AA × 2.1 treatments, respectively (Table 2). The seasonal mean diurnal curves for the O_3 treatments show the progression of concentrations throughout the day and illustrate the proportional nature of the additions (Fig. 2).

Environmental Conditions and Moisture Treatments

The 1986 growing season was exceptionally hot in July, wet and cool in mid-to-late August, and very dry from mid-September through October (Table 1). The amounts of irrigation applied monthly and the soil matric potential measurements (Fig. 3) reflect those conditions. In October it was necessary to irrigate the CF and NF plots in the WW and WW-C treatments slightly more than the other O_3 treatments due to the greater leaf area and healthier condition of the leaves in those plots, resulting in a more rapid depletion of soil moisture. The greatest differentials in leaf water potential between the WW and WS treatments occurred during mid-July and mid-September (Fig. 3) when the plants were in the vegetative and podfill stages of growth, respectively (Table 1). Significant differences (at the 5% level) in leaf water potential among the different O_3 treatments occurred only on 2 of the 14 d measurements were made.

The effects of the open-top chamber with and without a rain exclusion cap on temperature and solar radiation were compared. From 0700 and 2100 h EST, the temperature in the middle of the soybean canopy was elevated an average of approximately 0.7 and 1.0 °C above that in nonchambered plots in the standard open-top and open-top with rain cap, respectively (Table 3). This agrees with the results of Heagle et al. (1979). The greatest divergence in temperatures between the two chamber types occurred in the afternoon. Solar radiation above the plant canopy (0800 – 1600 h EST) was reduced 9% (compared to nonchambered plots) by the normal chamber and by an additional 6% by the presence of the rain exclusion cap.

Ozone and Water Stress Effects on Injury and Yield Components

Visible injury to the eight uppermost mainstem leaves was usually greater as O_3 concentrations increased in all soil moisture treatments (Table 4). The

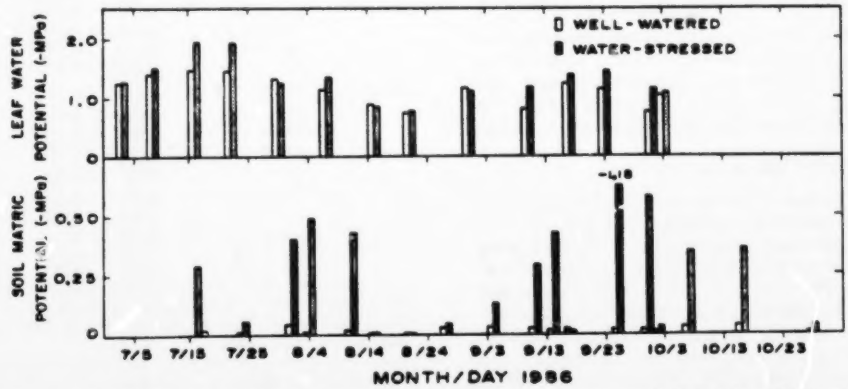

Fig. 3. Soil matric potential and leaf water potential in well-watered (WW) and water-stressed (WS) plots. Soil values are the mean of tensiometer readings in all WW plots (WW-C plots were nearly identical and thus not shown) and the mean of neutron probe readings (adjusted for soil moisture release curves) in all WS plots. Leaf water potentials values are the mean of 12 measurements taken midday in six plots (two leaves in both replicates of the CF, AA × 1.5, and AA × 2.1 plots) in both the WW and WS treatments.

Table 3. Comparison of chamber effects on temperature and solar radiation in standard open-top chambers and in open-top chambers with rain exclusion caps.†

Chamber type	Time of day (EST) 0700–0800	0900–1000	1100–1200	1300–1400	1500–1600	1700–2100	Reduction in solar radiation‡
	°C (above ambient)						%
Open-top	0.84	0.95	0.90	0.50	0.50	0.45	9
Open-top with cap	0.84	1.01	1.23	1.01	1.18	0.84	15

† Temperature measured in one WW and one WW-C chamber at height of 70 cm at five locations in soybean canopy from 19 September to 24 October. Values are the average differences between a chambered and a nonchambered plot for the hours listed.

‡ Average solar radiation measured at top of soybean canopy (0800–1600 EST) at a height of 140 cm from 11 to 30 September. Values are the percent reduction from measurements in a nonchambered plot.

injury estimates on 12 September indicated somewhat less injury at the three higher O_3 concentrations in the WS treatment compared to plots having the same O_3 concentrations in the WW and WW-C treatments. Less injury was found in the CF and NF plots in the WW-C treatments compared to the WW or WS treatments at the first two dates. Overall, the extent of injury due to O_3 was not extensively different among soil moisture treatments on the dates measurements were made.

Ozone and water treatment effects on yield components were significant in the AOV, with the exceptions of O_3 and water effects on seeds per pod and the water effect on weight per 100 seeds (Table 5). The O_3 × water interactions were not significant for any yield component. Suppression of seed yield by O_3 was due to effects on both the number of filled pods and the mass of individual seeds, whereas water stress suppressed only the number of filled pods (Table 6). The WW-C plots appeared to yield slightly better than the WW plots at all O_3 concentrations except AA × 1.8, although the differences were slight. An AOV using only the WW and WW-C treatment data did not indicate a significant difference in yield between these two sets of plots nor a significant interaction with O_3.

Polynomial and Weibull regression models were fit to the seed yield data (Fig. 4, Table 7). Three types of

Table 4. Mean percentage visible injury to mainstem leaves of 'Young' soybean exposed to different doses of O_3.

Soil moisture treatment†	O_3 treatment‡	12 Sept.	26 Sept.	10 Oct.
		% injury§		
WW	CF	12	20	50
	NF	15	37	66
	AA × 1.5	25	40	89
	AA × 1.8	41	66	98
	AA × 2.1	51	79	100
WW-C	CF	2	13	58
	NF	4	25	53
	AA × 1.5	27	50	79
	AA × 1.8	38	69	95
	AA × 2.1	50	85	100
WS	CF	10	25	58
	NF	13	30	74
	AA × 1.5	18	44	91
	AA × 1.8	34	61	99
	AA × 2.1	43	73	100

† WW = well-watered; WW-C = well-watered with caps; WS = water stressed.

‡ Charcoal-filtered (CF), nonfiltered (NF), and three proportional additions of 1.5, 1.8, and 2.1 times the ambient air (AA) concentration (AA × 1.5, AA × 1.8, and AA × 2.1, respectively).

§ Each value is the mean of 64 mainstem leaves (the eight uppermost leaves of four plants in two plots). Foliar injury was estimated visually as the percentage of chlorosis or necrosis.

Table 5. Mean squares (MS) from analyses of variance for yield components of soybean exposed to O_3 at three levels of soil moisture.

Source	df	No. of filled pods, no. m^{-1} MS	$P > F$	Weight of filled pods, g m^{-1} MS	$P > F$	Number of seeds, m^{-1} MS	$P > F$	Weight of 100 seeds, g MS	$P > F$	Seeds per pod MS	$P > F$	Seed yield, g m^{-1} MS	$P > F$
O_3	4	89 530	0.0001	89 515	0.0001	545 197	0.0001	28.3	0.0001	0.010	0.3065	47 891	0.0001
Water	2	101 491	0.0001	11 921	0.015	288 755	0.0024	0.048	0.951	0.017	0.1438	8 244	0.006
O_3 × water	8	7 299	0.356	3 090	0.261	47 306	0.2319	0.94	0.485	0.009	0.4091	1 573	0.271
Error A	15	6 027	–	2 157	–	31 197	–	0.95	–	0.008	–	0.008	–

Table 6. Effect of O_3 concentration and soil moisture treatment on yield components of 'Young' soybeans.†

Soil moisture treatment‡	Ozone treatment§	Seasonal 12 h d^{-1} mean O_3 conc.	No. of filled pods	Wt. of filled pods	No. of seeds	Wt. of 100 seeds	Seeds per pod	Seed yield
		μL L^{-1}	m^{-1}	g m^{-1}	m^{-1}	g		g m^{-1}
WW	CF	0.015	1463	716	3068	16.87	2.1	517
	NF	0.036	1480	749	3101	16.89	2.1	540
	AA × 1.5	0.057	1448	617	2885	15.06	2.0	440
	AA × 1.8	0.071	1232	487	2559	13.77	2.1	351
	AA × 2.1	0.083	1257	484	2616	13.15	2.1	345
WW-C	CF	0.019	1525	772	3395	16.52	2.2	559
	NF	0.039	1492	773	3083	17.91	2.1	551
	AA × 1.5	0.061	1479	645	3079	14.79	2.1	457
	AA × 1.8	0.070	1123	433	2251	13.62	2.0	309
	AA × 2.1	0.087	1267	496	2600	13.41	2.1	349
WS	CF	0.020	1248	639	2704	16.79	2.2	453
	NF	0.038	1319	651	2828	16.24	2.2	457
	AA × 1.5	0.059	1191	565	2663	15.02	2.2	400
	AA × 1.8	0.072	1123	495	2341	14.60	2.1	343
	AA × 2.1	0.084	1128	444	2319	13.42	2.1	309

† Each value is the mean for four sections of row (two in each of two replicates) converted to a 1.0 m of row basis. Seed moisture content was 8.6%.

‡ WW = well-watered; WW-C = well-watered with caps; WS = water-stressed.

§ Charcoal-filtered (CF), nonfiltered (NF) and three proportional additions of 1.5, 1.8, and 2.1 times the ambient air (AA) concentration (AA × 1.5, AA × 1.8, and AA × 2.1, respectively).

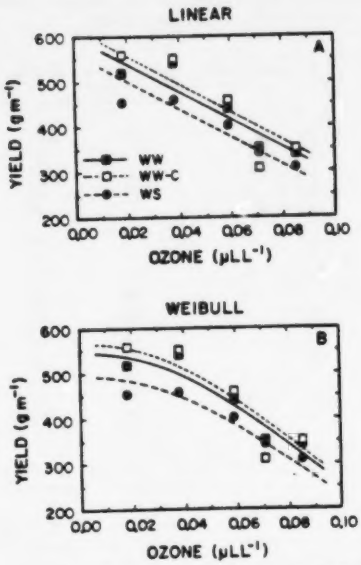

Fig. 4. Linear and Weibull dose-yield response curves for well-watered (WW), well-watered with rain exclusion caps (WW-C), and water-stressed (WS) plots. Equations for models are given in Table 7.

polynomial models were initially considered: (i) common intercepts and slopes for all moisture treatments, (ii) separate intercepts but common slopes, and (iii) separate intercepts and slopes. Tests comparing the three types of polynomial models rejected the hypothesis of common intercepts but accepted the hypothesis of common slopes. The most appropriate model proved to be a linear model (the quadratic term was not significant) combining all three soil moisture treatments with common slopes but different intercepts (Fig. 4a, Table 7). A similar set of model comparisons was made with the Weibull model [common parameters for all moisture levels, separate α values (intercepts), and separate parameters for all moisture levels]. The hypothesis of common intercepts was rejected, so the final model combined the three moisture treatments and had separate α values (y intercept) but common σ and c values (Fig. 4b, Table 7).

DISCUSSION

The response of Young soybean to O_3 was within the range of responses found in previous field studies with other cultivars (Kress and Miller, 1983; Kohut et al., 1986; Heagle et al., 1987) and as recently summarized by Heagle et al., 1988. For example, at a mean seasonal O_3 concentration (12 h d^{-1}) of 0.05 μL L^{-1}, the Weibull model estimated a yield suppression in the present study of 13% relative to a background O_3 concentration of 0.02 μL L^{-1}. Young was selected from a cross of 'Davis' and 'Essex' and, at similar O_3 doses, Weibull models estimated that the yield of these cultivars was suppressed about 7 to 19 and 15%, respectively (Heagle et al., 1988). With other cultivars the estimated yield suppression has ranged from 0 to 21% at similar O_3 doses. While at least 12 O_3 dose-yield response studies with nine cultivars of soybean have been performed at several locations in the USA, the

Table 7. Linear and Weibull regression models for soybean seed yield (g m^{-1} of row) in response to O_3 and water stress†

Linear model

$$\underset{(17)}{\text{Yield} = 601\ M_1} + \underset{(18)}{562\ M_2} + \underset{(18)}{617\ M_3} - \underset{(258)}{3108\ O_3}$$

Weibull model

$$\underset{(21)}{\text{Yield} = (545\ M_1} + \underset{(20)}{492\ M_2} + \underset{(22)}{567\ M_3)} \exp\left[-(O_3 / \underset{(0.0079)}{0.1127})^{\underset{(0.485)}{2.217}}\right]$$

† Analyses for both models do not include ambient air plots. Weibull model: yield = $\alpha \exp[-(O_3 / \sigma)^c]$, where α is the maximum yield at O μL L^{-1} O_3, σ is the O_3 concentration when yield is 0.37 α, and c is a dimensionless shape parameter. The O_3 concentration is the seasonal 12 h d^{-1} mean. The quadratic term in the polynomial model was not significant and, thus, not included. The M_1, M_2, and M_3 terms account for the soil moisture treatments, where $M_1 = 1$ (M_2 and $M_3 = 0$), $M_2 = 1$ (M_1 and $M_3 = 0$), or $M_3 = 1$ (M_1 and $M_2 = 0$) for WW, WS, and WW-C treatments, respectively. Values in parentheses are standard errors for the estimates.

relative cultivar sensitivity to O_3 is still not well defined. Year-to-year and site-to-site variation in response to O_3 has made cultivar comparisons difficult. Due to limitations in plot size and the availability of chambers, only a few studies have compared multiple cultivars in the same experiment (Heggestad et al., 1985, 1988; L.W. Kress, 1988, personal communication). Even with these studies, too little field data exist to draw any firm conclusions regarding relative O_3 sensitivity of soybean cultivars.

Whereas water stress suppressed the yield of Young soybean, it did not significantly alter the yield response to O_3 (i.e., the O_3 × water interaction was not significant). In previous studies examining the influence of water stress on the response of soybean to O_3, significant O_3 × water interactions occurred in some experiments but not in others (Heagle et al., 1988). In the present study the effect of water stress was moderate, causing a 12% suppression of yield in the well-watered CF plots compared to the water-stressed CF plots. These findings are similar to those from a study with Davis soybean in Raleigh, NC, where an O_3 × water interaction did not occur when yield was suppressed 22% in the CF plots by water stress (Heagle et al., 1987). In another year of study with Davis, however, a significant interaction was inferred since O_3 suppressed yield in well-watered plots but not in water-stressed plots (Heagle et al., 1988). In the latter case, water stress suppressed yields by 43% in the CF plots. Similarly, a significant O_3 × water interaction was observed with 'Corsoy' soybean at Argonne, Il, when water stress suppressed yield 32% at the lowest O_3 concentration (L.W. Kress, 1988, personal communication). From these limited results it would seem that a significant interaction (reduction of the impact of O_3 by water stress) may be most likely to occur with more severe water stress conditions. A study with Corsoy and 'Williams' soybean in Beltsville, MD, suggested that suppression of yield by near-ambient O_3 concentrations may be accentuated by water stress (Heggestad et al., 1985). In this same study, however, water stress appeared to protect the plants from O_2-induced yield loss at higher O_3 concentrations (Heggestad et al., 1988).

We can only speculate on the reasons for the differences in O_3 × water interactions among experiments. Different cultivars were used in most experiments and environmental and cultural conditions

differed across sites and/or years. As discussed above, the severity of the water stress imposed on the plants is another consideration, and certainly the timing of the water stress episodes may be important in determining the extent or type of interaction. Edaphic differences, specifically those limiting rooting depth, have been proposed to account for differences among experiments, as well (Heggestad et al., 1988).

The physiological bases for reduction of plant sensitivity to O_3 by water stress are not firmly established although it is likely that effects on gas exchange through the stomates play a large role. Under conditions of severe water stress, O_3 uptake by the leaves can be extensively reduced due to stomatal closure (Tingey et al., 1982; Tingey and Hogsett, 1985). So, at comparable O_3 treatment concentrations, water-stressed plants receive a smaller, physiologically effective dose, which would result in less O_3-induced stress. It is also possible that water-stressed plants may be less physiologically responsive to a given internal O_3 dose due to biochemical and/or anatomical changes, although Tingey and Hogsett (1985) present evidence to the contrary.

Another objective of the present study was to determine the feasibility of using permanently installed rain exclusion caps on open-top chambers to enable greater control of soil moisture in the plots. The main concern was that the additional modification of the microenvironment due to the cap would influence yield response of the crop to O_3. The use of permanent rain exclusion caps reduced light and increased temperature slightly compared to standard open-top chambers, but significant effects on soybean yield due to the caps were not observed. Most importantly, from the standpoint of using the caps in future studies of $O_3 \times$ water stress interactions, the caps did not change the yield response of soybean to O_3. Similar results were found previously in a field study of the effects of shading on O_3 dose-response relationships with pot-grown soybean (Heagle and Letchworth, 1982). In the present study, other nondestructive measures of plant growth and development were made on the WW and WW-C treatments. None of the measures (e.g., height, number of nodes, V or R stage, percent visible injury, or mainstem leaf retention) indicated a substantial effect of the rain exclusion cap on growth or development compared to plants in standard open-top chambers (S.F. Vozzo, 1988, personal communication). The similarity in growth and yield in the WW and WW-C treatments at a range of O_3 concentrations is further evidence that slight alterations in the microenvironment do not substantially change crop response to O_3 stress.

Additional studies are needed to further characterize $O_3 \times$ water stress interactions and, more explicitly, to identify environmental and edaphic conditions under which these interactions occur. Ideally, these studies should use a range of water stress conditions in a single experiment to eliminate the influences of other environmental factors, such as those that occur when experiments are repeated across years and locations. The timing and duration of water stress episodes is of great concern and these variables should be investigated, as well. When possible, several cultivars of varying sensitivity to O_3 and/or water stress should be used within a single experiment.

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